



APPARATUS AND METHOD FOR POLARIZING
POLARIZABLE NUCLEAR SPECIES

The instant application claims the benefit of U.S. Provisional Application Serial

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Field of the Invention

The present invention is in the field of hyperpolarizing polarizable nuclear species, such as xenon.

Background of the Invention

Nuclear magnetic resonance (NMR) is a phenomenon, which can be induced through the application of energy against an atomic nucleus being held in a magnetic field. The nucleus, if it has a magnetic moment, can be aligned within an externally applied magnetic field. This alignment can then be transiently disturbed by application of a short burst of radio frequency energy to the system. The resulting disturbance of the nucleus manifests as a measurable resonance or wobble of the nucleus relative to the external field.

For any nucleus to interact with an external field, however, the nucleus must have a magnetic moment, i.e., non-zero spin. Experimental nuclear magnetic resonance techniques are, therefore, limited to study of those target samples, which include a significant proportion of nuclei exhibiting non-zero spin. Certain noble gases, including Xenon, are in principle suited to study via NMR. However, the low relative natural abundance of these isotopes, their small magnetic moments, and other physical factors have made NMR study of these nuclei difficult if not impossible to accomplish.

Existing technology for polarizing xenon, developed primarily at Princeton, is based on earlier work on nuclear polarized ^3He gas targets for nuclear physics. The key

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component of the system is the polarizing chamber where the ^3He gas is heated, saturated with rubidium, an alkali metal vapor, and illuminated with laser light. In these devices, a closed cell of ^3He gas, rubidium, and nitrogen is maintained at a uniform high temperature to achieve an appropriate rubidium density. A laser illuminates the cell with circularly polarized light at the resonant absorption line of the rubidium, polarizing the rubidium electrons. Spin exchange occurs with the ^3He gas nucleus, leading to an accumulation of nuclear polarization. ^3He gas atoms diffuse throughout the cell.

Xenon polarization proceeds by a similar mechanism. Circularly polarized laser light polarizes rubidium atoms, which in turn transfer their polarization to the xenon nucleus. Xenon, however, has a large depolarization effect on rubidium. Therefore the partial pressure of xenon must be kept low. Diode lasers, which are used to illuminate the gas mixture, have a large linewidth. In order to more efficiently absorb more of this laser light, the rubidium should be in a high-pressure gas to pressure-broaden the absorption line. Princeton researchers use a high-pressure buffer gas of helium. They slowly flow a mixture of xenon, nitrogen, and helium through the polarizing cell. A sufficient quantity of rubidium is available in the polarizing cell. The unpolarized gas slowly enters this chamber and diffusively mixes with rubidium vapor and partially polarized gas already in the chamber. Rubidium condenses as the gas exits and cools down.

The use of a high-pressure buffer gas, such as helium, causes pressure broadening of the absorption spectrum of the rubidium, allowing greater extraction of laser power in a compact pumping cell with low rubidium density. Operation at high-pressure, however, changes the dominant mechanism for transferring polarization from the rubidium to the xenon. At high pressures the dominant mechanism is the two-body interaction. At low

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pressures, the mechanism mediated by three-body formation of molecules dominates which is considerably more efficient. Consequently, the improvement in polarization achieved by the gain in laser efficiency is partially offset by a reduction in rubidium-xenon polarization transfer.

Existing polarization techniques also use a gas mixture dominated by helium at high pressure. The high pressure of helium broadens the absorption linewidth of the rubidium, allowing it to usefully absorb more of the linewidth of the diode laser. If they reduce the pressure, they would not absorb as much light in their short polarizing cells. If they lengthened their cells using their diffusively mixed process, they would mix gas from regions with an even greater range of polarization rates. If the existing process could be performed effectively at low pressure, however, the polarization system would be capable of taking advantage of the higher efficiently molecular formation physics.

Existing polarization methods cannot efficiently use the full polarizing power of the laser beam. The gas mixture attenuates the laser light. Consequently, the region of the polarizing cell farthest from the laser will only achieve low rubidium polarization if the cell is long. Since the gas in the polarization cell is diffusively mixed, the xenon will achieve an average polarization that is influenced by both the high rubidium polarization and the low rubidium polarization. To minimize the region of low rubidium polarization, the laser must exit the polarizing cell after using only a portion of its polarizing power.

Summary of the Invention

The present invention results from the realization that by using a longer than standard polarizing cell and flow within the cell dominated by laminar displacement, polarizing

polarizable nuclear species can be accomplished at low pressure with high temperature and high velocity, thereby taking advantage of the higher efficiency molecular formation physics.

It is therefore an object of this invention to dominate the flow through the cell by laminar displacement.

It is a further object of this invention to polarize polarizable nuclear species with high velocity.

It is a further object of this invention to increase efficient use of resonant light.

It is a further object of this invention to polarize polarizable nuclear species with high temperature.

It is therefore an object of this invention to polarize polarizable nuclear species at low pressure.

Brief Description of the Invention

The novel features believed characteristic of the invention are set forth in the claims. The invention itself however, as well as other features and advantages thereof, will be best understood by reference to the description which follows, read in conjunction with the accompanying drawings, wherein:

FIG. 1 shows a flow diagram with one embodiment of the inventive polarization method.

FIG. 2 shows a flow diagram of another embodiment of the inventive polarization method.

FIG. 3 shows one embodiment of the inventive polarization cell.

FIG. 4 shows a layout of one embodiment of the polarization apparatus.

FIG. 5 shows a layout of another embodiment of the polarization apparatus.

FIG. 6 shows a layout of another embodiment of the polarization apparatus.

Detailed Description of the Invention

The present invention is a polarizing process 10 involving a number of steps as shown in Figure 1. The first step requires moving 12 a flowing mixture of gas 52, the gas 52 at least containing a polarizable nuclear species and vapor of at least one alkali metal, with a transport velocity that is not negligible when compared with a natural velocity of diffusive transport. The second step is propagating 14 laser light 40 in a direction 58, preferably at least partially through a polarizing cell 30. The next step is containing 18 the flowing gas 52 mixture in the polarizing cell 30. The final step is immersing 20 the polarizing cell 30 in a magnetic field. These steps can be initiated in any order, although moving 12 the flowing gas 52, propagating 14 the laser 40 and immersing 20 the magnetic field must be concurrently active for the polarizing process 10 to occur.

The inventive method 10 can be refined in a number of different embodiments. One narrower embodiment involves the polarizing cell 30 having a length 62 substantially greater than its transverse dimension 64, such that the shape of the polarizing cell 30 directs 16 the moving 12 of the flowing gas 52 along a direction 54 generally opposite to the direction 58 of laser light 40 propagation 14.

Another narrower embodiment involves the polarizing cell 30 having a length 62 substantially greater than the laser 40 attenuation length, thereby causing efficient transfer of polarization from the laser 40 to the alkali metal vapor, even at low operating pressure where the most efficient alkali-polarizable nuclear species polarization transfer mechanism dominates.

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Another narrower embodiment involves the transport velocity of the flowing gas 52 being substantially greater than the natural velocity of diffusive transport.

Another narrower embodiment of the inventive method 10 involves the polarizing cell 30 having an operating gas pressure that is less than two atmospheres but greater than a pressure required to efficiently quench an alkali optical pumping using a combination of at least 2 torr of a polarizable nuclear species and a minimum pressure of a quenching gas, typically 60 torr of nitrogen.

Another narrower embodiment involves the magnetic field being uniform and substantially aligned with the direction 58 of laser light 40 propagation 14.

Another narrower embodiment of the inventive method 10 includes the additional step of condensing 22 the alkali metal vapor from the gas mixture 52 in the propagating 14 laser light 40. A narrower embodiment of this embodiment involves the condensation 22 occurring in an extension 70 of the polarizing cell 30 that is collinear with the polarizing cell 30, and through which the laser 40 propagates 14, thereby providing continuous polarization of the alkali metal vapor up to and during condensation 22. Another narrower embodiment of this embodiment involves the resulting condensed rubidium droplets coming to rest in either a saturating region 66, a region of the polarizing cell 30 heated by the oven 56, or both.

Another narrower embodiment involves the laser light 40 entering the polarizing cell 30 by passing through a window 38 of the polarizing cell 30 which is at a temperature substantially lower than that of the polarizing cell 30, thereby reducing attenuation of the laser light 40 in an unpolarized alkali metal vapor layer in contact with the window 38.

Another narrower embodiment of the inventive method 10 includes the additional step of saturating 24 an original gas mixture 68 with the alkali metal vapor to create the flowing gas 52 before the flowing gas 52 enters the polarizing cell 30.

A final narrower embodiment of the original inventive method 10 involves the polarizing cell 30 operating at a temperature that is greater than 150°C, thereby allowing faster polarization time constants and higher achievable polarization than existing practice.

The present invention also includes an inventive polarizing cell 30. The polarizing cell 30 is a nonferrous enclosure 32 with an interior 34 and at least two openings 36 for flowing gas 52 to pass through the enclosure 32. The polarizing cell 30 further includes a window 38 in the enclosure allowing laser light 40 to at least partially illuminate the interior 34. The unique feature of the polarizing cell 30 is that the window 38 is maintained at a temperature substantially lower than most of the enclosure 32.

The present invention also includes an inventive polarizing apparatus 50. The inventive apparatus 50 includes a polarizing cell 30 with multiple openings 36, and at least one window 38 transparent to laser light 40. The apparatus further includes a flowing gas mixture 52, at least containing a polarizable nuclear species, at least one alkali metal vapor, and at least one quenching gas, moving 12 through the cell 30 in a direction 54. The apparatus 50 further includes an oven 56 at least partially containing the polarizing cell 30. The apparatus 50 further includes a laser propagating 14 light 40, at the absorption wavelength of the alkali metal vapor, through at least one transparent window 38 into the polarizing cell 30 in a direction 58 at least partially opposite to the direction 54 of the flowing gas mixture 52. Finally, the apparatus 50 includes an optical arrangement 60 to cause the laser light 40 to be substantially circularly polarized.

The inventive apparatus 50 also has several narrower embodiments. One of the narrower embodiments involves having the oven 56 only partially containing the polarizing cell 30. A narrower embodiment of this embodiment involves using the previously described inventive polarizing cell 30 having the window maintained at a temperature substantially lower than most of the enclosure. Having the polarizing cell 30 sized so that it is more than five times greater in length 62 than diameter 64 can further narrow this embodiment. In one embodiment, the cell can be ninety centimeters in length 62 and two centimeters in diameter 64.

Another embodiment of the apparatus 50 involves the oven 56 maintaining a temperature of over 150C.

Another embodiment of the apparatus 50 includes having a saturation region 66 with a quantity of liquid alkali metal exposed to an original gas mixture 68 to substantially saturate 24 the original gas mixture 68 with an alkali metal vapor to create the flowing gas mixture 52 that flows 12 through the polarizing cell 30.

Another embodiment of the apparatus 50 includes having a condensation extension 70 of the polarizing cell 30, through which the laser 40 propagates 14, before passing through a remainder 72 of the polarizing cell 30, for condensing 22 the alkali metal vapor in the laser light 40.

Another embodiment of the apparatus 50 includes composing the alkali metal vapor of rubidium, cesium and/or potassium.

Another embodiment of the apparatus 50 includes making the quenching gas nitrogen and/or hydrogen.

Existing practice in the polarization of polarizable nuclear species relies on the achievement of equilibrium conditions throughout the polarization chamber. The static polarization process of Rosen, Chupp et al uses very long (20 min) polarization time constants by selecting low temperature (90C) and low rubidium density. Consequently they can use high xenon concentrations (more than one atmosphere). The quasistatic polarization process of Cates, Happer, et al uses shorter time constants (5 min) in a flowing system. By selecting higher temperature (up to 150C) they have higher rubidium density. They must reduce their polarizable nuclear species pressure to a few percent of their working pressure of 10 atmospheres to maintain high rubidium polarization. The gases in their polarization chamber are diffusively mixed.

In contrast to existing practice, the present invention uses flowing gases 52 whose flow velocity is not negligible when compared with the natural velocity of diffusive transport. We specify the present invention using this language because diffusion times are pressure dependent. Taking advantage of the transport will significantly improve performance over a wide range of pressures, both in existing operation regimes as well as in a preferred embodiment. Diffusion across a typical one-inch dimension requires one second at a pressure of one-tenth of an atmosphere and ten seconds at ten atmospheres in a typical gas mixture. The transport velocity is not negligible when compared with this velocity if it is, for example, greater than one-half this velocity. In a more favorable embodiment, the transport flow velocity will be several times this velocity, i.e. several inches per second. To achieve polarization in this regime requires polarization time constants more than one order of magnitude higher than the highest used in present practice, on order several seconds or faster. This requires higher rubidium densities to achieve faster time constants.